

Matter Distribution around Galaxies

Shogo Masaki¹, Masataka Fukugita^{2,3,4}, Naoki Yoshida⁴

ABSTRACT

We explore the mass distribution of material associated with galaxies from the observation of gravitational weak lensing for the galaxy mass correlation function with the aid of N -body simulations of dark matter. The latter is employed to unfold various contributions that contribute to the integrated line of sight mass density. We conclude that galaxies have no definite edges of the matter distribution, extending to the middle to neighbouring galaxies with the density profile roughly $r^{-2.4}$ beyond the virial radius. The mass distributed beyond the virial radius (gravitationally bound radius) explains the gap seen in the mass density estimates, the global value $\Omega_m \sim 0.27$ and typically $\Omega_{\text{gal}} \sim 0.15$ from the luminosity density multiplied by the mass to light ratio. We suggest to use a physical method of gravitational lensing to characterise galaxy samples rather than characterise them with photometric means.

Subject headings:

1. Introduction

Where and how is matter distributed in the Universe is a long-standing question. The widely accepted view is that matter of the universe is preponderantly borne by galaxies. This leads to an estimate of the mass density of the Universe (Ostriker et al. 1974). With modern parameters, the luminosity density $\mathcal{L} = 2.2 \pm 0.3 \times 10^8 h L_\odot \text{Mpc}^{-3}$ (Blanton et al. 2001;2003) multiplied by the average mass to light ratio of galaxies, $\langle M/L \rangle \approx (170 \pm 50) h M_\odot / L_{r_\odot}$, from the gravitational lensing shear around 2×10^4 galaxies (McKay et al. 2001) leads to the mass density of the Universe $\rho_m = \mathcal{L} \times \langle M/L \rangle$ as,

$$\Omega_m = 0.13 \pm 0.05 \quad (1)$$

in units of the critical mass density. The mass of M/L we adopted here is supposed to represent the virial mass, i.e., the mass of particles gravitationally bound in galaxies. This M/L is consistent among a number of estimates for individual galaxies (e.g., Bahcall & Fan 1998).

¹Department of Physics, Nagoya University, Chikusa, Nagoya 464-8602, Japan; masaki@a.phys.nagoya-u.ac.jp

²Institute for Advanced Study, Princeton, NJ08540, U. S. A.

³Institute for Cosmic Ray Research, University of Tokyo, Kashiwa 277-8582, Japan

⁴Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwa 277-8583, Japan

On the other hand, we now have a convincing estimate of the global matter density from the cosmic microwave background radiation anisotropy (Komatsu et al. 2011), which converges to

$$\Omega_m = 0.27 \pm 0.03. \quad (2)$$

The difference between Eqs. (1) and (2) raises the problem as to where is half the matter missing, indicated by the mismatch of the two numbers.

Within the bound radius of galaxies, the mass distribution is inferred to obey the profile close to the one advocated by Navarro, Frenk & White (1997, hereafter NFW) in the CDM dominated universe. Simulations of clustering of dark matter conveniently point towards this distribution for mass assemblies. This is also supported by gravitational lensing analysis for bright galaxies (Mandelbaum et al. 2006). Little is studied, however, concerning the mass distribution beyond the virial radius.

Observational advancement with large galaxy samples lends gravitational weak lensing to a powerful tool to explore the average surface mass density of galaxies. The measure is the surface density $\Sigma(R)$ as a function of the projected radius from the centre of the galaxy R ,

$$\Sigma(R) = \int \rho \left(r = \sqrt{R^2 + \chi^2} \right) d\chi, \quad (3)$$

where ρ is the density at r and χ is the line of sight distance, both measured from the centre of the galaxy. This quantity can be explored along the line-of-sight towards a light source by measuring its tangential shear γ_t or magnification μ of the image of background sources, as

$$\gamma_t(R) = \frac{\bar{\Sigma}(< R) - \Sigma(R)}{\Sigma_{\text{cr}}} = \frac{\Delta\Sigma(R)}{\Sigma_{\text{cr}}}, \quad (4)$$

$$\mu(R) \simeq 1 + 2\kappa(R) = 1 + 2\frac{\Sigma(R)}{\Sigma_{\text{cr}}}, \quad (5)$$

where $\bar{\Sigma}(< R)$ is the average of Σ within R , κ is the convergence, and $\Sigma_{\text{cr}} = (c^2/4\pi G)(D_s/D_{\ell s}D_{\ell})$ is the critical surface density.¹ With the modern large samples this is applicable even to the outskirts of galaxies significantly beyond the virial radius, say to $\sim 10h^{-1}$ Mpc using either lensing shear (Sheldon et al. 2004; Mandelbaum et al. 2006; Reyes et al. 2010) or statistical magnification (Ménard et al. 2010). While thus obtained $\Sigma(R)$ includes the surface mass density from neighboring galaxies along the line of sight, this quantity gives a cogent information as to the surface mass density profile of the galaxy away from its central region.

Ménard et al. (2010, hereinafter MSFR) have shown that $\Sigma(R)$ decreases approximately as $R^{-\beta}$ with $\beta = 1 \pm 0.2$ to $R < 1h^{-1}\text{Mpc}$, which somewhat flattens to $\beta = 0.6 \pm 0.4$ beyond $R \approx 1h^{-1}\text{Mpc}$ to $10h^{-1}\text{Mpc}$ using galaxy samples of the Sloan Digital Sky Survey (York et al.

¹Eq. (5) is the Taylor expansion to the first order in distortion. Ménard et al. (2003) examined the accuracy of the formula with the conclusion that the higher order terms contribute by about 10-15 percent to magnification.

2000; Abazajian et al. 2005) . They used the correlation of magnification signal of background quasars with foreground galaxies. They also showed that the surface density profile derived from the magnification agrees with that from the tangential shear of galaxies (Sheldon et al. 2004). Mandelbaum et al. (2006) have also derived the surface mass density profile for the luminous red galaxy (LRG) sample, which lies parallel to that of MSFR for $R < 1h^{-1}\text{Mpc}$, however, with their amplitudes about 2.5 times larger than that of MFSR. The difference of the surface mass density of the two profiles diminishes as the distance and the two agree at $R > 1h^{-1}\text{Mpc}$, albeit with substantial errors in the measurements.

In this paper we study the distribution of matter around galaxies with the aid of an extensive use of N -body simulations for the CDM dominated universe without baryons, which have been convergent among different simulations to a sufficient accuracy. We employ N -body simulations to unfold contributions from multiple galaxies and to interpret the finding from gravitational lensing, but also to extrapolate the physics to the region beyond the reach of the observation after verifying that the N -body simulation indeed describes the observed surface mass density profile with an accuracy sufficient to us. We note that Hayashi & White (2008) also used large numerical simulations to study the dependence of the galaxy/halo-matter cross-correlation amplitude on the galaxy mass and the halo mass. We expect that the state-of-the-art N -body simulation for dark matter gives information that is sufficiently reliable for the quantity where the observations would not directly give the information, if the simulation is appropriately constrained by the observation. This gives insight as to the distribution of the matter beyond the observation, and would tell us concerning the more global distribution of matter in the Universe considerably away from galaxies.

In section 2 we describe the N -body simulation. In section 3 we present the surface mass density profile in reference to the observation. We discuss the mass distribution beyond the virial radius and notify that a caution is necessary as to the aperture when the mass of galaxies is referred to in section 4. Section 5 is a summary of our analysis.

2. Cosmological N -body simulations

We use the parallelised N -body simulation code *Gadget-2* (Springel et al. 2001; Springel 2005) in its Tree-PM mode. Baryons are not included. We assume the flat universe with the cosmological parameters $\Omega_m = 0.258$ and $h = 0.719$, the Hubble constant in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$; for other parameters $n_s = 0.963$ and $\sigma_8 = 0.796$, following the parameters derived in the WMAP 5-year result (Komatsu et al. 2009). The gravitational softening parameter is chosen to be $\epsilon = 10h^{-1}\text{kpc}$. We take 1024^3 particles in a box of comoving $200h^{-1}\text{Mpc}$ on a side. The mass of a dark matter particle is $5.34 \times 10^8 h^{-1} M_\odot$, so that we are able to identify halos with mass a few times $10^{10} h^{-1} M_\odot$. We set the initial redshift at $z_i = 50$ and generate the initial condition using the

second-order Lagrangian perturbation theory²(Scoccimarro 1998), which has the advantage that it is more accurate to generate initial conditions so that one can set them at an epoch later than with the conventional Zeldovich approximation; see Crocce et al. (2006); Jenkins (2010). The initial matter power spectrum at $z = z_i$ is computed using the *CAMB* code (Lewis, Challinor & Lasenby 2000).

Halo es are identified in two-steps. We select candidate groups of dark matter particles using the friend-of-friends algorithm, where we take the linking length to be $b = 0.2$. We then apply the spherical overdensity algorithm to the candidate groups that are identified by friend-of-friends. We choose groups that contain at least 100 particles. We follow the conventional operational definition for the pseudovirial radius (r_v): when the particles enclosed within some radius give the average mass density $200 \times \rho_{\text{crit}}(z)$, they form a halo, the mass of which is given by the sum of those particles and is referred to as the virial mass M_v . Taking the minimum number of particles in a halo to be 100, i.e., the minimum mass of the halo is $5.3 \times 10^{10} h^{-1} M_\odot$, we identify 229,804 halo es. Table 1 shows the number of halo es we identified in the simulation at $z = 0.36$, which is the average redshift of the galaxy sample used by MSFR.

We confirmed that the halo mass function agrees with modern simulations at a good accuracy, e.g., with that by Crocce et al. (2010), but also with the analytic formula of Sheth & Tormen (1999) with a known slight deviation as reported by the above reference. We fit all groups with the NFW profile and compare the concentration parameter $c = r_{\text{vir}}/r_s$ (r_s is the scale length of the NFW profile) as a function of halo mass with other modern simulations. We confirmed that our c agrees with that of Macciò et al. (2008) (see also Bullock et al. (2001)) within a few percent level. The simulations are well converged and the difference in simulations and analysis algorithms is tolerably small.

The scale range that concerns in this paper is $20h^{-1}$ kpc or larger, where the contribution from baryons modifies little the surface mass density profile. Hence, we confine ourselves to the CDM universe without baryons.

²The parallelised second-order Lagrangian perturbation theory code (Nishimichi et al. 2009) is provided by T. Nishimichi.

Table 1: Halo es identified in our simulation at $z = 0.36$.

mass [$h^{-1} M_\odot$]	number	number fraction [%]	mass fraction [%]
$5 \times 10^{10} - 5 \times 10^{11}$	189,578	82.5	5.9
$5 \times 10^{11} - 5 \times 10^{12}$	36,402	15.8	8.25
$5 \times 10^{12} - 5 \times 10^{13}$	3,637	1.6	7.64
$5 \times 10^{13} - 5 \times 10^{14}$	187	0.08	3.13

3. Surface mass density profiles around haloes

We calculate the mean surface mass density around haloes in the following way. We shift the entire box so that it is centred on a halo being considered. We consider a beam and project the mass of simulation particles within comoving $100h^{-1}\text{Mpc}$ widths to the beam. This gives the surface mass density around the beam at a specific projected distance. We then take the average of the beams around all haloes to obtain the projected surface mass density profile.

Figure 1 compares our simulation for the surface mass density at $z = 0.36$ with the observational result of MSFR which was derived at the same mean redshift. The abscissa is the physical distance at this redshift from the centre of the halo. The simulation is represented by a bunch of thin curves for 100 haloes randomly chosen from the 9970 haloes that have a virial mass larger than $2 \times 10^{12}h^{-1}M_{\odot}$ (this choice is discussed below). The maximum halo mass in our simulation is $5 \times 10^{14}h^{-1}M_{\odot}$. The thick solid curve is the average over the entire sample above the mass threshold. The observational data (ticks with error bars) are taken from MSFR. The simulation agrees with the observation very well, in both overall shape and amplitude up to $10h^{-1}\text{Mpc}$.

The dashed curve shows the contribution from the central haloes which are truncated at their virial radii, the so-called one-halo term. The figure shows that the mean surface density at $R \lesssim 200h^{-1}\text{kpc}$ is dominated by the one-halo term. We note that our column integrates over all particles along the line of sight and it would receive the contribution not only from the tail of neighbouring haloes but also from possible ‘unbound’ particles away from galaxies.

To separate the contributions of bound and unbound particles, we remove the particles beyond the virial radii of all haloes. Then we recompute the surface mass density in the same way as described above, but including haloes with mass below our virial mass threshold set above. This is shown in Figure 2 with the dash-dotted curve, which stands for the contributions from bound particles in all haloes. The data, the thick solid and the dashed curves are the same as in Figure 1. The figure shows a substantial difference between the solid and dash-dotted curves, meaning that particles bound in haloes contribute only by 1/3 the total surface mass density beyond the distance of $\approx 500h^{-1}\text{kpc}$ from the galaxy. We remember that the total surface mass density derived in the simulation agrees with that estimated from gravitational lensing. Roughly 2/3 the surface mass density at such a distance is due to particles residing beyond the virial radius of any galaxies, i.e., gravitationally ‘unbound’ particles.

In our argument we set the cutoff on the lowest mass of haloes, somewhat arbitrarily, at $2 \times 10^{12}h^{-1}M_{\odot}$. This choice should of course affect the surface mass density profile. We show in Figure 3 the mass density profiles with different threshold mass: $5 \times 10^{11}, 2 \times 10^{12}, 5 \times 10^{12}, 2 \times 10^{13}, 5 \times 10^{13}h^{-1}M_{\odot}$. We see that the surface mass density increases as the lower cutoff mass (virial mass) M_{low} increases for small radii, say, $R < 1h^{-1}\text{Mpc}$ where the one halo term is the significant contributor. The result of the simulation shows $\Sigma(R) \propto M_{\text{low}}^{2/3}$ for the distance scale 10kpc to a few

hundred kpc: it is summarised, e.g., at $120h^{-1}\text{kpc}$ as

$$\Sigma \simeq 100(M_{\text{low}}/8 \times 10^{12}h^{-1}M_{\odot})^{2/3}hM_{\odot}(\text{pc})^{-2}. \quad (6)$$

With the singular isothermal sphere we have the surface mass density at the projected distance R ,

$$\Sigma(R) = \left(\frac{25\pi}{6}\rho_{\text{crit}}\right)^{1/3} M_v^{2/3} \frac{1}{R}, \quad (7)$$

and a similar relation holds with the NFW profile albeit in the limited distance range. With our mass function the average mass $\langle M_v \rangle \approx 5M_{\text{low}}$, so that our fitting formula eq.(6) gives for a given $\Sigma(R)$ a halo mass 2.5 times smaller than the model with the singular isothermal sphere.

This sample threshold dependence explains the difference in the surface mass density distributions between Mandelbaum et al. (2006), which are also plotted in Figure 3, and MSFR. The former gives $\Sigma(R)$ larger by a factor of 2.5 than MSFR within a few hundred kpc range. Equation (6) then indicates that the threshold mass of the LRG sample of Mandelbaum et al. (2006) is approximately by 4 times more massive than that of MSFR, who used the main galaxy sample. The difference seen in $\Sigma(R)$ among different halo masses diminishes for a large R , where the one halo term no longer dominates but $\Sigma(R)$ is contributed by neighbouring haloes and unbound particles, as seen by comparing $\Sigma(R)$ of Mandelbaum et al. (2006) and MSFR.³ (Neighbouring haloes are more likely to be those of normal galaxies rather than LRGs.)

Figure 3 indicates that the mean surface mass density profile around galaxies measured by MSFR is reproduced well when the threshold mass M_{low} is set to $2 \times 10^{12}h^{-1}M_{\odot}$, which is approximately the mass of the L^* galaxy $1.2 \times 10^{12}h^{-1}M_{\odot}$ (Fukugita & Peebles 2006); hence our default cutoff is chosen. MSFR used the galaxy sample $17 < i < 21$. If the effective cutoff of the sample would be around $i \approx 20$, sample's threshold is around the L^* galaxy⁴(Blanton et al. 2001).

It is less ambiguous to estimate the threshold mass from $\Sigma(R)$ itself. With the threshold $2 \times 10^{12}h^{-1}M_{\odot}$, $\Sigma(R)$ of the simulation is in good agreement with the data. If we would take the threshold $5 \times 10^{11}h^{-1}M_{\odot}$, which roughly corresponds to the $i \approx 21$ mag threshold, $\Sigma(R)$ of the simulation would lie somewhat too low. This consideration suggests that the surface mass density can be used to characterise the mass of the galaxy sample, which otherwise is difficult to estimate accurately.

In the limited range of the distance scale we are studying, $15\text{kpc} < R < 200\text{kpc}$ both NFW and singular isothermal sphere give mass profiles that are very similar and both give good fits to the data, so that we are not able to distinguish between the two profiles in this range.

³ The LRG data show a slightly larger amplitude at $R \sim 1h^{-1}\text{Mpc}$, reflecting greater bias. The overall features of the surface density profiles for different galaxy/halo masses are studied in detail by Hayashi & White (2008).

⁴ At a more accurate level we must consider that L^* luminosity corresponds to $10^{10.6}L_{\odot}$ in the i band, while it does to $10^{10.5}L_{\odot}$ in the r band. L^* luminosity is not physically well defined. We also note that there is a significant uncertainty in the mass-luminosity relation associated with morphology of galaxies.

4. Mass distribution beyond the virial radius

We see above that the substantial amount of matter in the Universe resides outside the pseudovirial radius of galaxies. In order to examine whether the distribution of unbound particles is organised, we calculate the total amount of mass encircled with the pseudovirial radius, and then expand the encircling radius by a factor of α : we denote it in units of the critical density as $\Omega_{\text{halo extended}}(\alpha)$. The pseudovirial radius is defined for each galaxy as 200 times ρ_{crit} . For a large α two haloes start overlapping, and in such cases we count the amount of material only once, avoiding double counting. Figure 4 shows the fraction $\Omega_{\text{halo extended}}(\alpha)/\Omega_m$ as a function of α , which is described well with $0.23 \ln \alpha + 0.22$ consistent with the NFW profile in its $\rho \sim r^{-3}$ regime.

If the mass distribution of a galaxy were spatially bounded, it would not matter for the mass estimate of galaxies whatever the encircling radius is taken in so far as it is large enough. We find, however, this is not the case. The encircling radius must be carefully specified, for instance, to calculate the mass to light ratio to be quantitatively meaningful.

The figure shows that the matter within the pseudovirial radius ($\alpha = 1$) is only 0.25 times the total matter if the sample of galaxies is set above the mass threshold $10^{11} h^{-1} M_{\odot}$, above which the galaxy mass (and hence M/L) is observationally estimated; see below. This fraction (and the curve in the figure) depends on the threshold mass of sample galaxies, as $\sim -\log M_{\text{low}}$ in so far as M_{low} is taken below the break mass of the mass function. If the threshold is taken at a larger mass, this fraction decreases faster, mainly because the number of galaxies included in the sample decreases. Note that the sample threshold must be taken small enough to estimate the mass density of the universe so that the contribution of sub-threshold galaxies to the global quantity (in practise luminosity density) is not substantial. We confirm that this mass fraction agrees with the mass obtained by integrating over the mass function. The figure also shows that this fraction becomes close to 0.5 if 3 times the pseudovirial radius is taken to encircle clustering. Almost entire matter ($> 90\%$) is included only with $\alpha > 20$.

Now it may be appropriate to examine the case discussed by McKay et al. (2001), who estimated the mass of galaxies from gravitational lensing shear, as we quoted earlier. They used the spectroscopic sample of SDSS, which means the limiting magnitude accurately defined at $r_{\text{limit}} = 17.8$ (Strauss et al. 2002). It corresponds to $M_r \approx -20.6$ for the median redshift of the sample $z \approx 0.10$ with the median K correction, or to $0.41 L_r^*$. If we invoke an empirical scaling relation $M \propto L^2$ (Mandelbaum et al. 2006) as consistent with the Faber-Jackson relation, we estimate the limiting mass of the sample $M_{\text{low}} \approx 2 \times 10^{11} h^{-1} M_{\odot}$, taking $M_{\text{MW}} \approx 2.3 \times 10^{12} M_{\odot}$ (Fukugita & Peebles 2006) and $L_{\text{MW}} = 1.4 L_*$ for the Milky Way to normalise the $M - L$ relation.

This can also be verified from the gravitational lensing measurement itself. McKay et al. (2001) obtained $\Sigma(R) \approx 2.5(R/1h^{-1}\text{Mpc})^{-0.8 \pm 0.2} h M_{\odot} \text{pc}^{-2}$. Consulting with our $\Sigma(R)$ relation with the sample threshold mass as a parameter (see Figure 3), we estimate $M_{\text{low}} \approx 1.5 \times 10^{11} h^{-1} M_{\odot}$ in agreement with the photometric estimate.

With this threshold we estimate the mean virial mass of the spectroscopic sample approximately $\overline{M}_v \approx 1.5 \times 10^{12} h^{-1} M_\odot$ using the mass function obtained in our simulation. This value is compared with the estimate $\overline{M}_v \approx 2.6 \pm 1.3 \times 10^{12} h^{-1} M_\odot$ of McKay et al. (2001) for their sample, where the error includes the variance associated with the galaxy morphology. This shows the consistency of the two estimates, those by McKay et al. (2001) and ours.

Our simulation gives the average pseudovirial radius over the sample with the lower mass cutoff M_{low} as $\bar{r}_v = 100 h^{-1} \text{kpc} (M_{\text{low}}/10^{11} h^{-1} M_\odot)^{0.29}$, so that our estimate of the virial radius \bar{r}_v for the sample with $M_{\text{low}} \approx 1.5 \times 10^{11} h^{-1} M_\odot$ is $\bar{r}_v = 120 h^{-1} \text{kpc}$. McKay et al. (2001) claim that they measured the M/L within $260 h^{-1} \text{kpc}$, which is $\alpha \approx 2.2$ times the mean virial radius of the sample. Figure 4 tells us that for $\alpha = 2.2$ approximately 0.4 times the total Ω_m should be included in their estimate. This leads us to the global matter density from galaxies to be

$$\Omega_m = (0.13 \pm 0.05)/0.4 \approx 0.32, \quad (8)$$

which is consistent with the global value of Eq.(2). Although our estimate presented here is admittedly crude, this agreement indicates that the mass beyond the pseudovirial radius we inferred here is probably broadly correct. We should underline the importance of the estimate of the radius (e.g., with respect to the virial radius) when the mass or the mass to light ratio is presented for galaxies, since galaxies are extended objects without definite boundaries.

We next calculate the volume occupied with extended haloes as a function of α . In Figure 5 we plot the fraction of mass contained in the extension of haloes $\Omega_{\text{halo extension}}(\alpha)/\Omega_m$ as a function of the fraction of the volume occupancy $V_{\text{halo extension}}(\alpha)/V_{\text{total}}$, where V_{total} is the total simulation volume. The numbers beside the symbol indicates the multiplier α . $V_{\text{halo extension}}$ is approximately proportional to $(\alpha R)^3$ up to overlaps of haloes at a large α . This figure shows that the plot is given nearly by a straight line, indicating that

$$\Omega_{\text{halo extension}}(\alpha)/\Omega_m \sim [V_{\text{halo extension}}(\alpha)/V_{\text{total}}]^{0.2} \quad (9)$$

Let us recall if the mass distribution is random throughout the entire volume we expect $\Omega_{\text{halo extension}} \propto V_{\text{halo extension}}$. The figure shows that there is no symptom of a conspicuous break of the curve at any α , meaning that the distribution of unbound matter is all organised to a distance significantly away from the galaxy, without leaving a significant amount of material in the intergalactic space. This power means that the matter density behaves as

$$\rho_m \sim r^{-2.4}, \quad (10)$$

beyond the virial radius, as long as halfway to the neighbouring galaxy. This drops faster than the isothermal profile but is numerically consistent with the tail of the NFW profile in the range $r/r_s = 5 - 100$ with r_s the NFW scale radius. Remembering that $r_v/r_s \approx 5$ for galaxies and the typical spacing between the galaxies is $r_0 \approx 5 h^{-1} \text{Mpc}$, the relevant range matches the inter-galaxy distance.

Since galaxies have no clear edges, it is not appropriate to define their ‘total’ mass. If we include the mass in the tail of the galaxy halfway to the neighbouring galaxy, the mass of galaxy increases approximately by a factor of 2 so that the effective M/L becomes $\approx 350hM_{\odot}L_{\odot}^{-1}$. When multiplied by the luminosity density $\mathcal{L} = 2.2 \times 10^8 hL_{\odot}\text{Mpc}^{-3}$, we would obtain

$$\rho_m = \mathcal{L} \times \langle M/L \rangle \approx 0.3\rho_{\text{crit}}, \quad \Omega_m \approx 0.3. \quad (11)$$

We remark that clusters serve as a good natural integrator of the mass of galaxies. The mass of clusters is usually estimated at the radius, say, r_{500} which is far beyond the virial radii of individual member galaxies. Therefore mass of galaxies resided in the tail is largely integrated in the estimate of the cluster mass. This explains the reason why M/L of clusters reaches 300–400, significantly larger than the estimates for individual galaxies: the mass here includes the mass present in the tail of galaxies. This explains the reason why we are arrived at the correct global mass density of the Universe, if the *cluster* M/L is used to multiply on the luminosity density of *field* galaxies instead of M/L of individual galaxies, though this is apparently an incongruous treatment.

5. Summary

We showed that the state of the art N -body simulation of dark matter based on the Λ CDM model gives an excellent description of the surface density profile of the mass distribution around galaxies, which has been explored up to the $10h^{-1}$ Mpc scale from the galaxy mass correlation function using weak gravitational lensing analysis applied to large modern galaxy samples. The surface profile thus derived is consistent with $r^{-1\pm0.2}$ up to $1h^{-1}\text{Mpc}$ and somewhat flattens to $r^{-0.6\pm0.4}$ beyond this radius. The latter power is consistent with that of the two point correlation function of galaxies. The galaxy mass correlation function measures the mass distribution within the galaxy halo in a short distance scale (smaller than a few $\times 100$ kpc scale) and reflects the galaxy distribution beyond this radius. The two distributions are similar and match each other with a slight break.

The amplitude of the surface mass density profile depends on the galaxy sample, in particular on the lower mass cutoff applied to the sample. Hence the amplitude serves us to infer the properties of the galaxy sample in a self-consistent way.

We showed that the galaxy has no clear edges in the dark matter distribution, unlike luminous matter, which should be bounded by the cooling radius. The distribution is extended beyond the virial radius in an organised way halfway to the neighbouring galaxy, so that the Universe is filled with the material associated with tails of galaxies, and we then call the peaks of the matter distribution galaxies. Inter-galactic space is filled with matter. Tails of galaxies extend to great distances without cutoff, whereas luminous component of galaxies have definite cutoff radius corresponding to the cooling radius.

About half the matter in the Universe is gravitationally unbound at $z \sim 0$. Its distribution,

however, is never random or uniform, but is well organised in a way to be consistent with the tail of galaxies with the mass density roughly $\rho \sim r^{-2.4}$. Half the matter is present in the tail of galaxies beyond the pseudovirial radius. This explains the gap in the estimate of mass density of the Universe between the global value and the value obtained by adding the contributions from matter bound to individual galaxies: with this extended matter distribution the matter entry closes in the mass inventory, which has been left unclosed in Fukugita & Peebles (2004)⁵.

The observables derived from gravitational lensing lend us to characterise the sample in terms of the mass with physical means. The agreement between photometrically inferred characteristics and physically derived ones is, if not perfect yet, nearly satisfactory. Gravitational lensing would be used to characterise the sample with physical methods.

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⁵ Fukugita & Peebles (2004) consider that 60% of matter is bound, i.e., within virial radii, and that the rest 40% lie outside. Their inference of these numbers uses M/L estimated by McKay et al. (2001), assuming that their encircled radii are sufficiently large to cover the binding radius, so that the used radius is 2.2 times the virial radius, as we discussed in the text above. In our present estimate 60% must be modified to 40% in the same context, and the bound component, if defined by the pseudovirial radius, is 25%.

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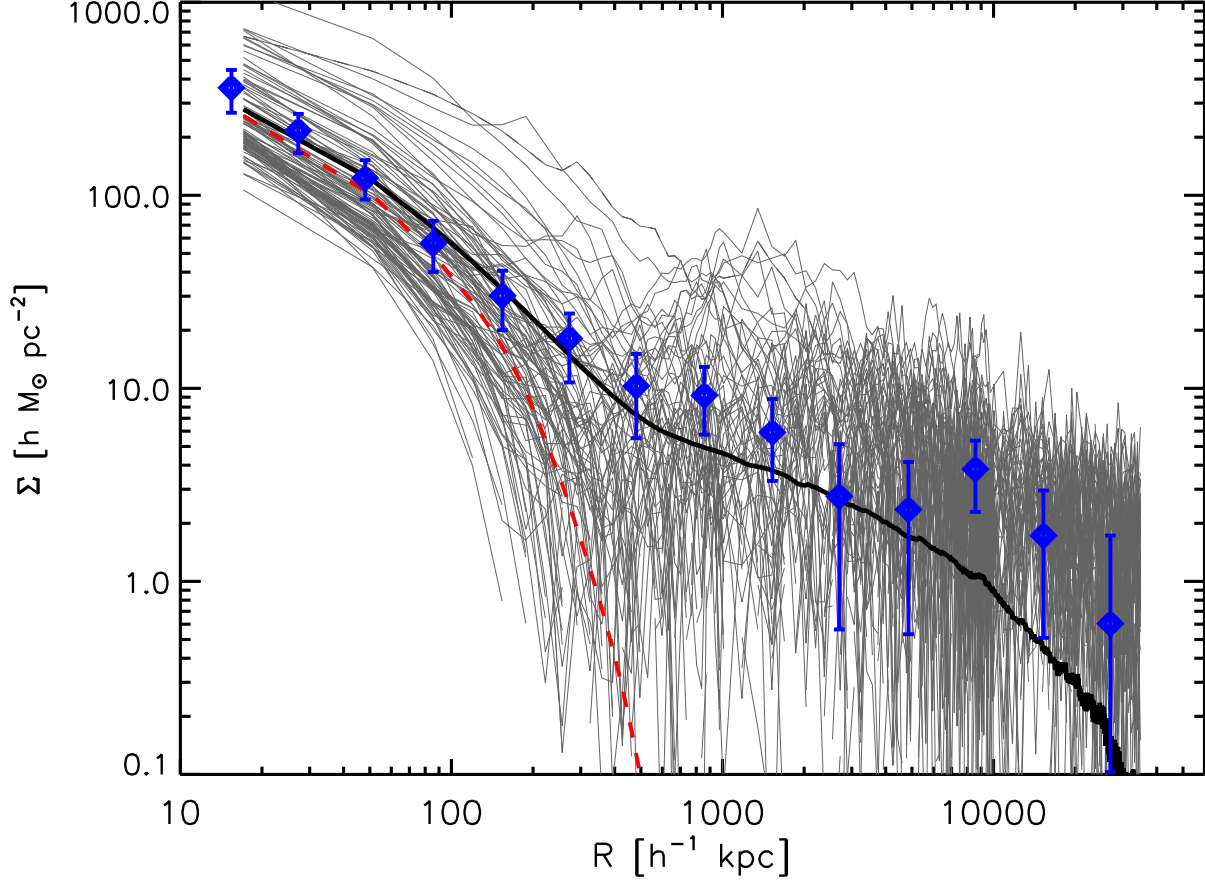


Fig. 1.— The surface mass density profile as a function of the distance from the centre of galaxies. The bunch of thin solid curves represent the profiles for 100 randomly picked-up haloes from 9970 haloes with mass $\geq 2 \times 10^{12} h^{-1} M_{\odot}$ generated in the Λ CDM N -body simulation. The thick solid curve is the mean of all haloes above the mass threshold. The dashed curve shows the contribution from the one-halo term. The data with error bars are the observational estimate using galaxy mass correlation function deduced from gravitational weak lensing for quasar brightness in MSFR. The abscissa is the physical distance at $z = 0.36$, which is the average redshift of the weak lensing observation.

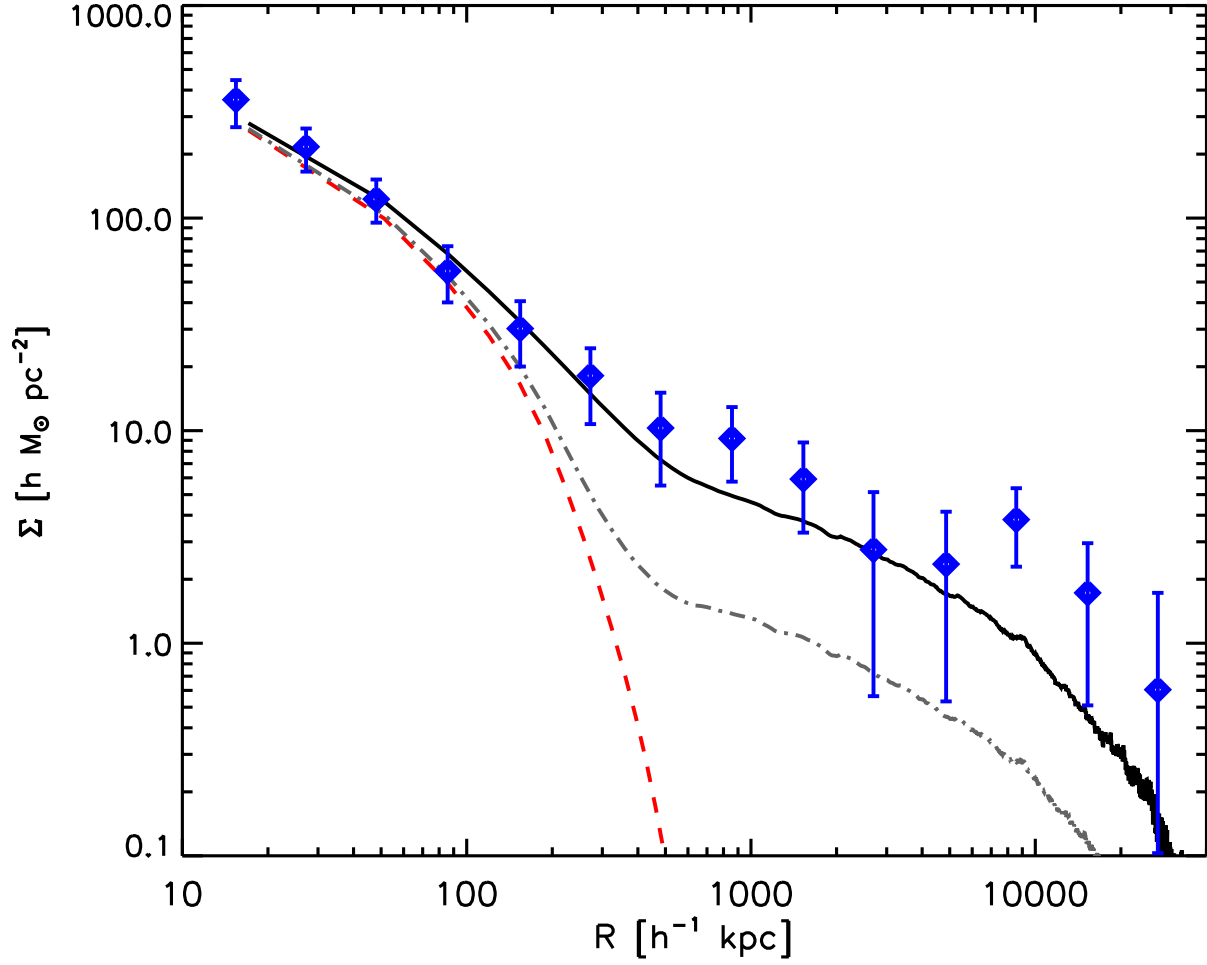


Fig. 2.— The mean surface mass density profile as a function of the distance from the centre of galaxies. The thick solid curve is the mean of all haloes above the mass threshold. The dash-dotted curve represents the contribution from particles bound to haloes, i.e., particles that reside within the virial radius of all haloes. The data with error bars are the observational estimate by MSFR as in the previous figure.

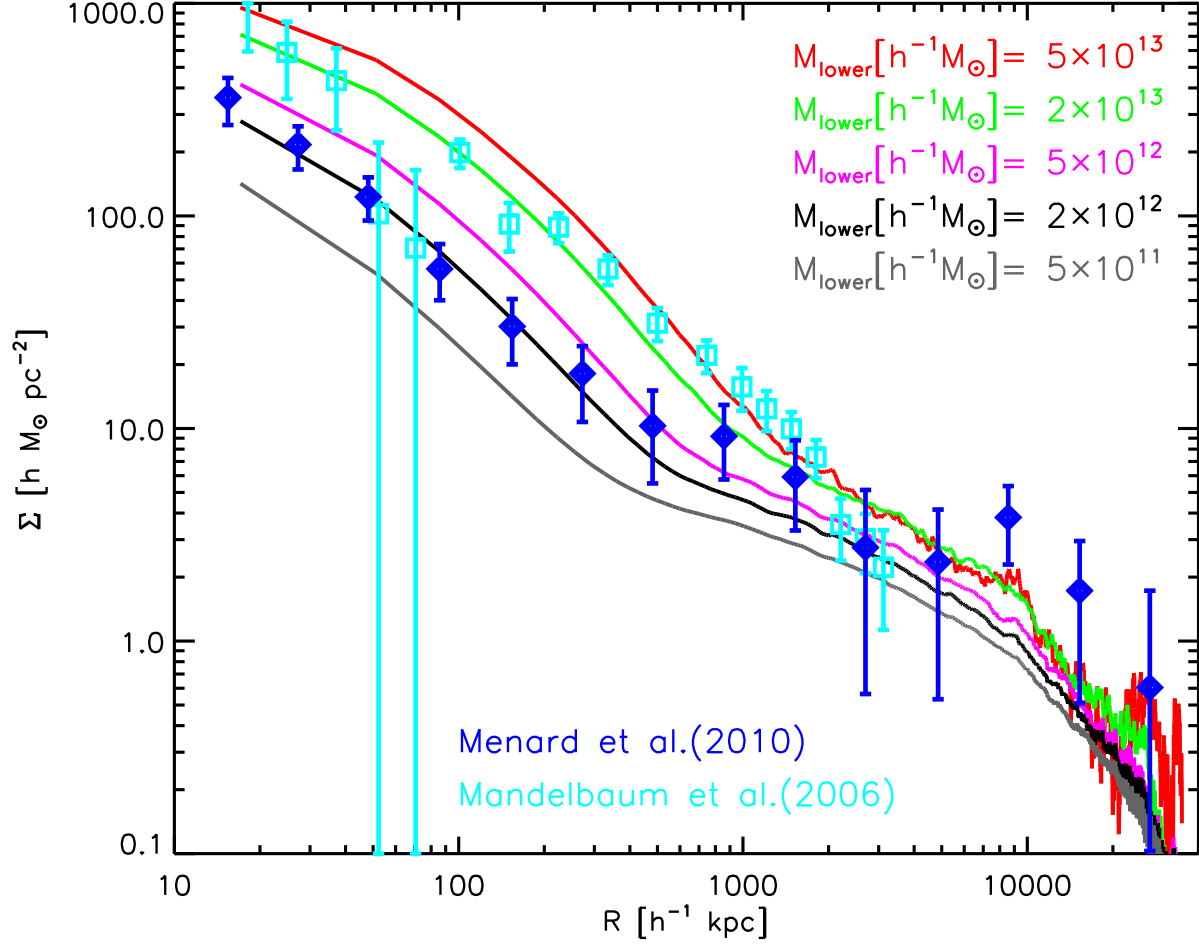


Fig. 3.— The mean surface mass density profile as a function of the distance from the centre of galaxies for galaxy samples with the different threshold halo mass (virial mass). The open squares which represent the data for LRG given by Mandelbaum et al. (2006) are added to the MSFR data for the SDSS main galaxy sample shown with solid diamonds with error bars.

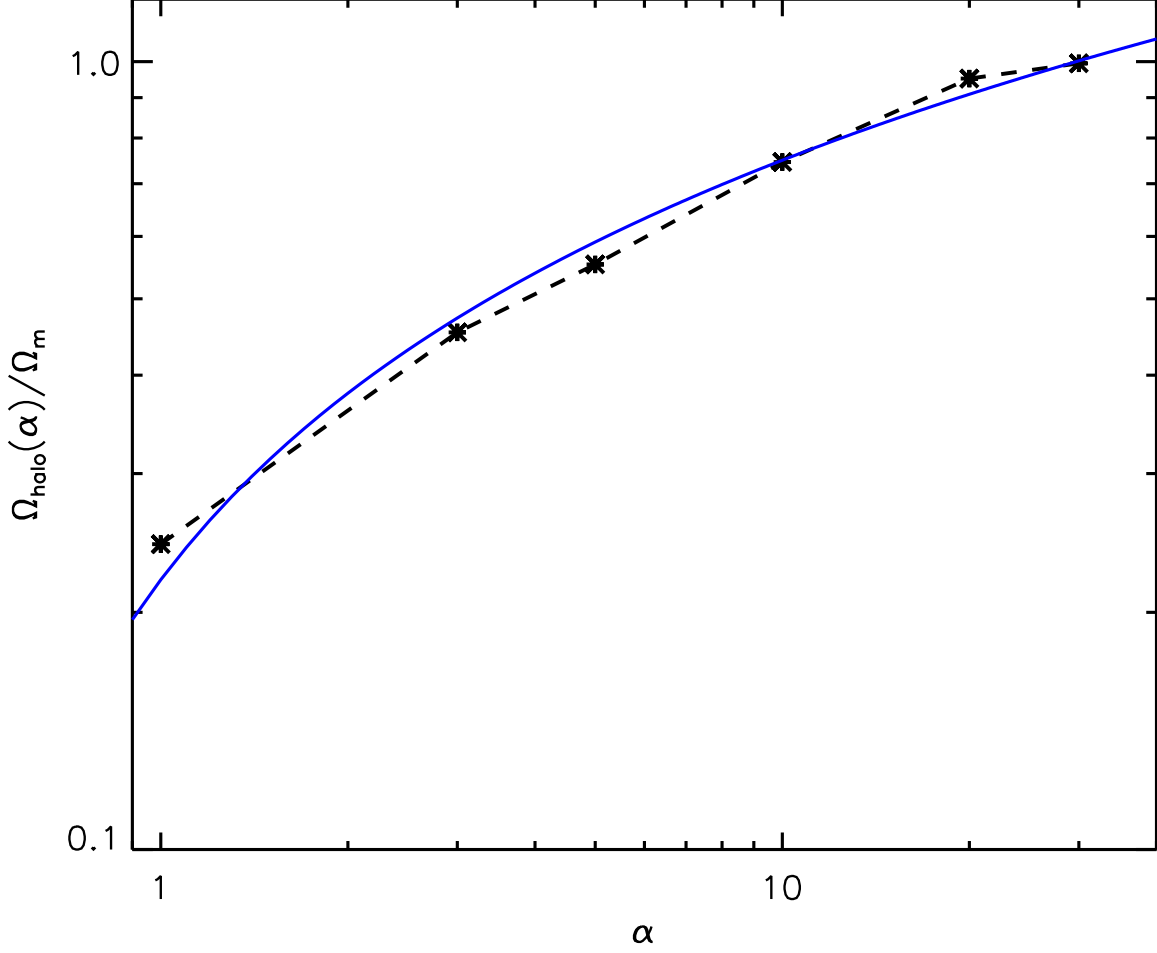


Fig. 4.— Fraction of mass contained in the sphere centred on individual haloes with radius αR_{vir} , where R_{vir} is the pseudovirial radius and α is the multiplier represented in the abscissa. The plot is for the sample with the threshold halo mass $1 \times 10^{11} M_{\odot}$. The solid curve is $0.23 \ln \alpha + 0.22$ given in the text.

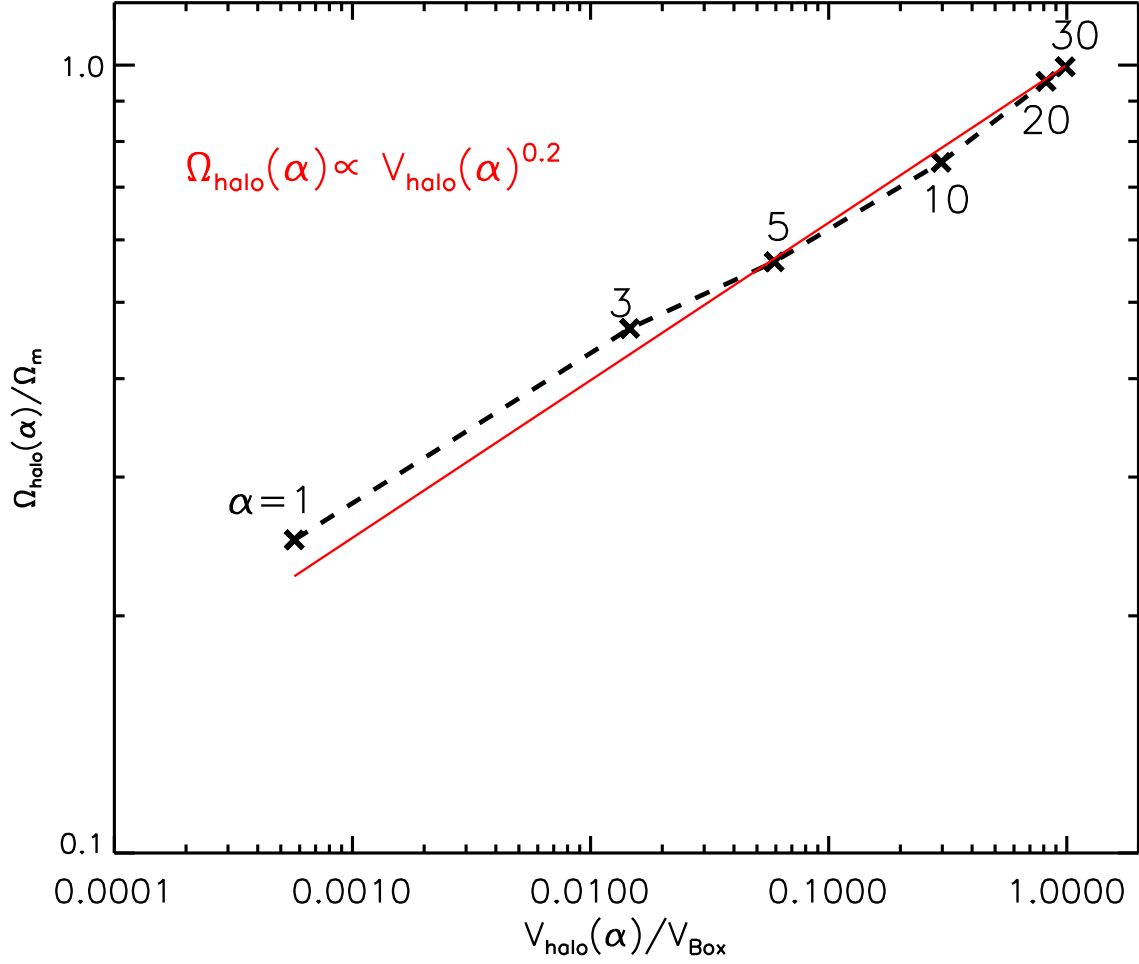


Fig. 5.— Mass fraction borne by extended haloes with the radius $r \leq \alpha R_{\text{vir}}$, $\Omega_{\text{halo extension}}(\alpha)/\Omega_m$ versus the volume fraction occupied by the extension of virial spheres $V_{\text{halo extension}}(\alpha)/V_{\text{tot}}$. The numbers shown beside the symbol is the multiplier α . The solid line indicates $\Omega_{\text{halo extension}}/\Omega_m \sim (V_{\text{halo extension}}/V_{\text{tot}})^{0.2}$.